Organic Carbon Budget of Fanning Island Lagoon[1]

DONALD C. GORDON, JR.[2]

ABSTRACT: The concentrations of total and particulate organic carbon in the waters of Fanning Island Lagoon are high and fairly uniform throughout, averaging 1.68 mg/liter and 80 μg/liter, respectively. Phytoplankton and reefs in the lagoon produce 7.8×10^4 kg of organic carbon daily, giving a turnover time of only 11 days for organic carbon. Only 0.4 percent of the daily production is lost from the lagoon by tidal exchange, the remainder is respired by organisms in the lagoon. Fanning Lagoon is a rich and unique environment which, because of its low flushing rate of about 230 days, has little effect on the surrounding ocean.

ATOLLS are often referred to as biological oases in the aquatic deserts of the tropical and subtropical oceans. The high productivity of coral reef communities has been well illustrated by the classic studies of Sargent and Austin (1949) and Odum and Odum (1955). However, an atoll by definition consists of a lagoon as well as encircling reefs and islands. Therefore, an understanding of processes in lagoons is also necessary for comparing atolls with, and describing their effects on, the surrounding ocean.

The few measurements made (Sargent and Austin, 1949; Doty and Capurro, 1961) indicate that phytoplankton productivity in lagoons is generally low. With the exception of a few determinations by Odum and Odum (1955) and Johannes (1967) at Eniwetok, the concentrations of organic carbon in lagoons are unknown. In addition, nothing is known as to how much organic carbon a lagoon loses by water exchange.

The Fanning Island Expedition offered an excellent opportunity to construct an organic carbon budget for a Pacific atoll lagoon. The small size and enclosed nature of Fanning Lagoon (Fig. 1) made it easy to study the distribution of organic carbon within the lagoon and to monitor its exchange with the ocean.

METHODS

Both total and particulate organic carbon were measured at various locations and depths within the lagoon and at 3-hour intervals at each of the three passes during a 24-hour sampling program. Seawater for analyses was either dipped from the surface or collected with an *in situ* pump (Schiesser, 1970) suspended from a Boston Whaler. Station locations are shown in Figure 1. During the 24-hour study, samples at English Harbor were collected at Buoy 4 from the surface, 3 m, and 7 m (just off the bottom). At North and Rapa passes, which are only a few feet deep, only surface samples were collected.

Total organic carbon was determined by treating unfiltered water with the dissolved organic carbon method of Menzel and Vaccaro (1964), as modified by Strickland and Parsons (1968). Collected water was placed in 250-ml glass bottles and processed and autoclaved in the laboratory as soon as possible, usually within a few hours. The analyses were completed a month later in Hawaii.

Water for particulate organic carbon analyses was collected in 4-liter plastic bottles. Upon return to the laboratory, 1 liter was filtered through a precombusted 25-mm Gelman type A glass fiber filter (the remaining water was used for other analyses). After being rinsed with 5 ml of distilled water, filters were placed in numbered plastic petri dishes and frozen until return to Hawaii. Then, each filter was placed in a 10-ml glass ampoule containing 5 ml of low-carbon distilled water (prepared by saturating glass-

[1] Hawaii Institute of Geophysics Contribution No. 355. Financial support was provided by National Science Foundation grant GB-15581.

[2] Department of Oceanography and Hawaii Institute of Geophysics, University of Hawaii, Honolulu, Hawaii 96822. Present address: Marine Ecology Laboratory, Bedford Institute, Dartmouth, Nova Scotia, Canada.

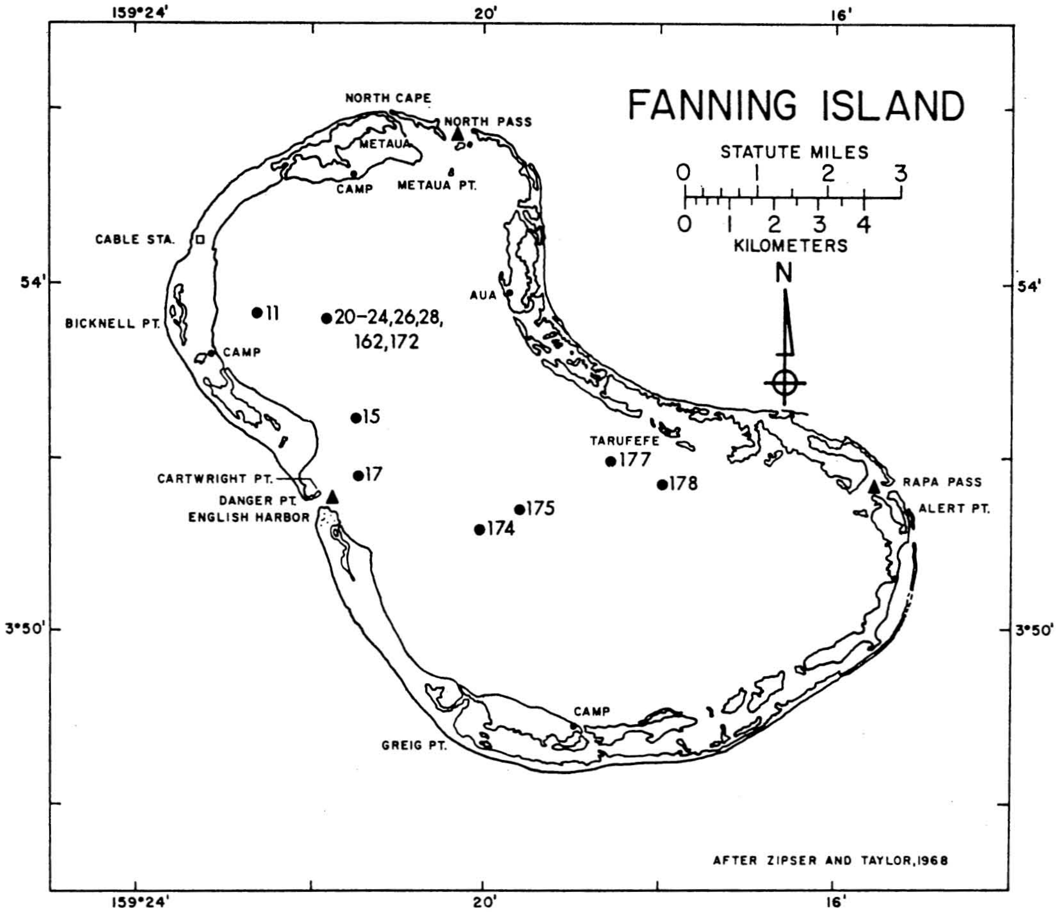

FIG. 1. Station locations at Fanning Atoll. The three triangles represent the stations during the 24-hr study.

distilled water with potassium persulfate and autoclaving for 1 hr) and treated like total organic carbon samples. The only differences in handling were that, for the determination of total organic carbon, twice as much potassium persulfate and phosphoric acid were added to each ampoule and a lower gain was used on the infrared carbon dioxide analyzer.

RESULTS

Lagoon Survey

The concentrations of both total and particulate organic carbon observed within the lagoon are plotted in Figure 2. Dissolved organic carbon concentrations can be obtained by subtracting the particulate from the total. As expected, the distributions of each were similar. Differences within the lagoon were evident, particularly between Stations 11, 15, and 17. Concentrations dropped as English Harbor was approached. At each station, concentrations were fairly uniform with depth. Temperature, salinity, and oxygen had a similar vertical distribution (Gordon and Schiesser, 1970), indicating that the water column was well mixed. In a few instances, sediment was stirred up when near-bottom samples were being collected. The particulate organic carbon concentrations of these samples (not recorded in Fig. 2) were several times greater because of organic carbon associated with the sediment.

Within the lagoon, the average total and particulate organic carbon concentrations were 1.68 mg/liter and 80 μg/liter, respectively.

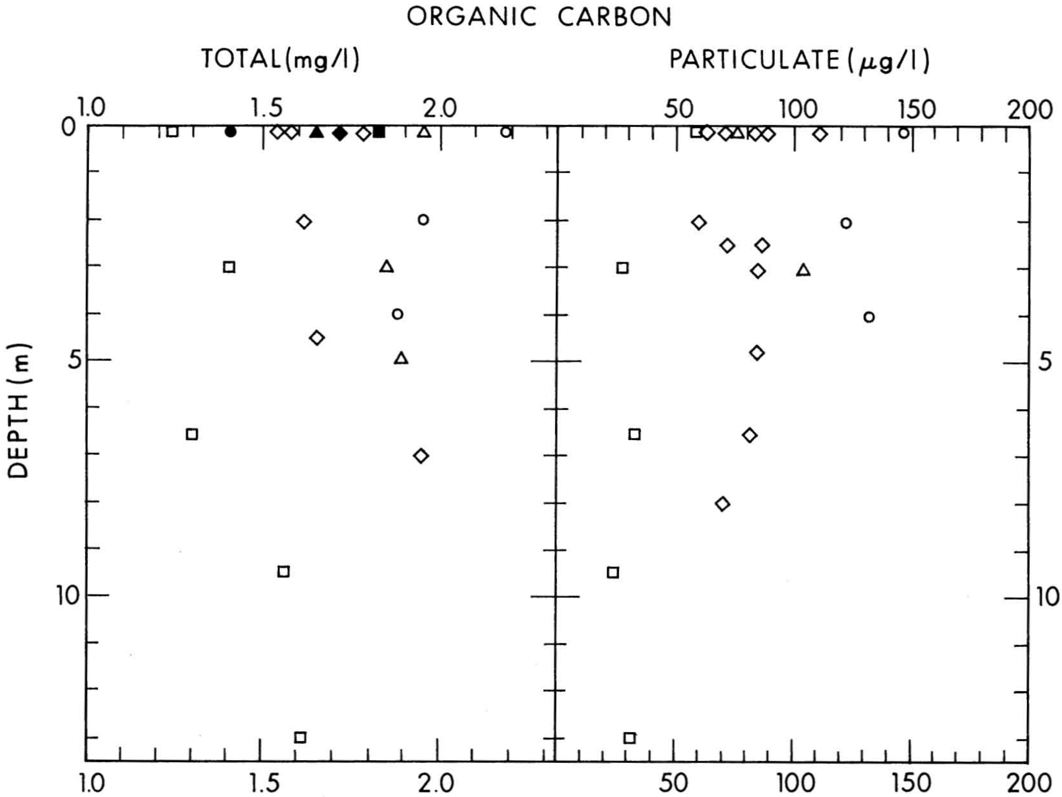

FIG. 2. Concentrations of total and particulate organic carbon in Fanning Lagoon. See Figure 1 for station locations. Stations 20–24, 26, 162, and 172 are in Suez Pond. ○, station 11; △, station 15; □, station 17; ◇, stations 20–24, 26, 162, and 172; ●, station 174; ▲, station 175; ■, station 177; ◆, station 178.

These mean values are much higher than those reported in the lagoon at Eniwetok. Odum and Odum (1955) reported an average total organic matter concentration of 1 mg/liter which is equivalent to a total organic carbon concentration of about 0.5 mg/liter, and Johannes (1967) observed an average particulate organic carbon concentration of 33.6 μg/liter just leeward of the Japtan interisland reef at Eniwetok. Thus, it is readily apparent that Fanning Lagoon is a much richer environment than Eniwetok Lagoon. The concentrations in Fanning Lagoon are, in fact, in the range of those reported by Klim (1969) just leeward of the main reef in Kaneohe Bay, Hawaii, a partially polluted embayment on the windward coast of Oahu.

Organic carbon concentrations in surface water changed near the line reefs which divide the lagoon into numerous ponds. Concentrations of both total and particulate organic carbon decreased steadily along a transect extending downwind from the line reef on the windward side of Suez Pond (Fig. 3), except for one anomalous particulate value. These gradients suggest that line reefs are contributing a sig-

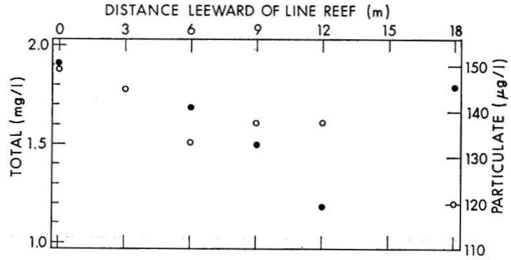

FIG. 3. Organic carbon concentrations at the surface along a transect downwind from a line reef in Suez Pond. Open and closed symbols denote total and particulate organic carbon, respectively.

nificant amount of organic carbon to lagoon water.

24-Hour Study

As expected, because the water column was well mixed, there were no significant changes of either total or partciulate organic carbon with depth at the English Harbor Station. Therefore, the three values at each sampling time were averaged. These averaged values are presented in Figure 4 along with the data from North and Rapa passes. The concentrations of both total and particulate organic carbon were much lower in the passes than in the lagoon, which indicates that the concentrations in the lagoon were higher than in the surrounding ocean.

Looking closely at the data (Fig. 4), a trend of higher ebb tide and lower flood tide concentrations becomes visible, particularly during the second half of the observations (Jan. 8). When the ebb and flood concentrations of both total and particulate organic carbon at each channel are averaged, the mean ebb concentrations are in fact greater than the mean flood concentrations in all cases. However, these

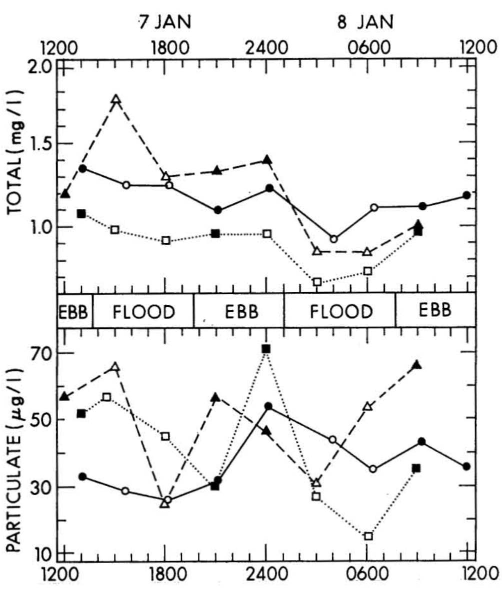

FIG. 4. Total and particulate organic carbon concentrations observed during the 24-hr study. Open and closed symbols denote flooding and ebbing tides, respectively. ○—●, English Harbor; △—▲, North Pass; □—■, Rapa Pass.

means were not significantly different when tested with a t-test. The data were then tested on the hypothesis that the differences between successive observations in different tidal stages were significantly different from zero. This test demonstrated that the particulate organic carbon differences were significant ($P = 0.05$), whereas those of total organic carbon were not. Thus, the lagoon was losing some particulate organic carbon through tidal exchange.

DISCUSSION

A crude budget for organic carbon in the waters of Fanning Lagoon can be constructed from the available data. Assuming that the processes affecting organic carbon in the lagoon are in equilibrium, production and import must be exactly balanced by export and respiration. This appears to be a reasonable assumption since atolls are generally considered to be ecological climax systems which, by definition, are quite stable.

Photosynthetic production by phytoplankton in the lagoon was measured by Gordon, Fournier, and Krasnick (Pacific Science, this issue) using the radiocarbon method. The average rate typical of the entire lagoon equaled 49 mg C/m^2/hr. This rate is approximately an order of magnitude greater than those previously reported from other Pacific atoll lagoons. Since the radiocarbon method is thought to measure principally net production, this figure is a meaningful estimate of the rate at which organic carbon was formed in the lagoon by phytoplankton activity. Assuming 12 hours of production daily and a lagoon area of 103 km^2, approximately 6.1×10^4 kg of organic carbon were produced each day by this process in the entire lagoon.

Some organic carbon in the lagoon water undoubtedly originated from the numerous line and patch reef communities which cover approximately 35 percent of the lagoon floor. This production is illustrated by the gradients of organic carbon in the vicinity of line reefs (Fig. 3). According to Johannes (1967), this exported material is principally mucus, and he calculated that it is produced at a rate of 0.02 g/m^2/hr on Japtan reef. Applying this rate to the Fanning Lagoon reefs, approximately 1.7 $\times$

10^4 kg of organic carbon should be released into the lagoon from reefs each day. This figure is certainly not accurate because of major differences between Japtan reef and the reefs in Fanning Lagoon. It is, however, a first approximation which, if anything, is probably too high.

It is significant to note that the phytoplankton in the lagoon were producing three times the amount of organic carbon exported by the reefs. Thus, the high concentrations of organic carbon in the lagoon were due principally to the high production rate of phytoplankton. The combined figures yield a daily total production of 7.8×10^4 kg of organic carbon for the entire lagoon.

Preformed organic carbon can be imported into the lagoon by two mechanisms: runoff and tidal exchange. Unfortunately, there are no data for the former. Runoff could be of some importance, however, because, except for the three narrow passes (Fig. 1), the lagoon is completely surrounded by vegetated land and the atoll does receive 81 inches of rain annually (Wiens, 1962). The quantity of organic carbon added by tidal exchange is calculated in Table 1. Because both North and Rapa passes are on the windward side of the atoll, there is a net inflow of water. Despite higher concentrations during ebb tides, there was also a net import of organic carbon amounting to 47 kg/day.

Export of organic carbon from the lagoon by tidal exchange is also calculated in Table 1. At English Harbor, where most of the water exchange occurred, 413 kg of organic carbon were lost daily. Subtracting the import of organic carbon at North and Rapa passes, there was a net export of 366 kg from the lagoon each day, all in the particulate form.

It should be noted that there is probably some water exchange through the atoll rim in the southeastern sector. This exchange is probably less than at Rapa Pass and should have little effect on the organic carbon budget of the entire lagoon.

Some organic carbon must also be lost to the sediments on the lagoon floor, but, as in the case of runoff, there is not sufficient data to calculate the rate of loss. It is assumed that this loss would be more or less balanced by the runoff input, so both items are omitted in the remainder of the discussion. The few analyses run (Schiesser, unpublished data) indicate the organic carbon concentration in Fanning Lagoon sediments is about 0.1 percent. Organic carbon could also be removed by fish coming into the lagoon to feed. This is logical to expect because of the much higher productivity in the lagoon than outside, but there are no data available to indicate whether this does or does not occur.

Balancing the above figures for production, import, and export, it is apparent that only 0.4 percent of the daily production of organic carbon was lost from the lagoon by tidal exchange. The remaining 99.6 percent must have been respired by organisms in the lagoon. This respiration rate is equivalent to 31 mg C/m^2/hr.

TABLE 1

NET ORGANIC CARBON FLUX DURING THE 24-HOUR STUDY

LOCATION	TIDE STAGE	MEAN POC (µg/l)	DAILY FLUX: WATER (m^3)	DAILY FLUX: ORGANIC CARBON (kg)	△ ORGANIC CARBON (kg)
English Harbor	flood	34	488×10^5	1,659	
	ebb	40	518×10^5	2,072	
					413 export
North Pass	flood	44	15.1×10^5	67	
	ebb	59	3.7×10^5	22	
					45 import
Rapa Pass	flood	36	7.5×10^5	27	
	ebb	47	5.3×10^5	25	
					2 import
					366 net export

NOTE: Daily water flux from Gallagher et al. (1971). Daily organic carbon flux determined by multiplying the mean particulate organic carbon concentrations (POC) for each tidal stage (Fig. 4) by the water flux.

Possible errors in estimating import and export have little effect on the conclusion that organic carbon cycling within Fanning Lagoon operates as a more or less closed system with only a slight loss to the surrounding ocean water. The rate of cycling was rapid, as the turnover time (total amount/production rate) of organic carbon was only about 11 days.

The principal reason for the small export of organic carbon from the lagoon is the apparently low flushing rate of the lagoon. The salinity data of Gordon and Schiesser (1970) and the organic carbon data herein indicate that inflowing oceanic water at English Harbor, where most of the tidal exchange occurs, did not mix appreciably with lagoon water before flowing out. However, from the tidal volume transport data of Gallagher et al. (Pacific Science, this issue), it is apparent that each day there was a net inflow at North and Rapa passes and a net outflow at English Harbor of approximately 22×10^5 m^3. Dividing this amount into the total lagoon volume gives a flushing rate of about 230 days. In contrast, Von Arx (1954) calculated a flushing rate of 35 days for Bikini Lagoon.

In conclusion, it is apparent that the biological processes in the lagoon play an important part in the total ecology of Fanning Atoll. A low flushing rate and a high rate of phytoplankton production have worked together to form a rich and unique environment.

ACKNOWLEDGMENTS

I wish to thank Glenn Shepherd for his help in collecting the lagoon and English Harbor samples, and Harold Schiesser for collecting and processing the total organic carbon samples at Stations 162–178. Alison Kay, Dick Stroup, Gerald Key, Keith Shimada, Carl Berg, and Joaquin Villagomez collected the samples at North and Rapa passes. Kenneth Binder assisted in the final stages of the total organic carbon analyses. I wish to thank Dr. R. E. Johannes for reviewing the manuscript.

LITERATURE CITED

DOTY, M. S., and L. R. A. CAPURRO. 1961. Productivity measurements in the world ocean. International Geophysical Year Oceanography Report No. 4.

GALLAGHER, B. S., K. M. SHIMADA, F. I. GONZALEZ, JR., and E. D. STROUP. 1971. Tides and currents in Fanning Atoll Lagoon. Pacific Science, vol. 25, no. 2, pp. 191–205, 12 figs.

GORDON, D. C., JR., R. O. FOURNIER, and G. J. KRASNICK. 1971. Note on the planktonic primary production in Fanning Island Lagoon. Pacific Science, vol. 25, no. 2, pp. 228–233, 1 fig.

GORDON, D. C., JR., and H. G. SCHIESSER. 1970. Temperature, salinity and oxygen observations at Fanning Island. Hawaii Institute of Geophysics Report 70-23.

JOHANNES, R. E. 1967. The ecology of organic aggregates in the vicinity of a coral reef. Limnology and Oceanography, vol. 12, pp. 189–195.

KLIM, D. G. 1969. Interactions between seawater and coral reefs in Kaneohe Bay, Oahu, Hawaii. Hawaii Institute of Geophysics Report 69-19.

MENZEL, D. W., and R. F. VACCARO. 1964. The measurement of dissolved organic and particulate carbon in seawater. Limnology and Oceanography, vol. 9, pp. 138–142.

ODUM, H. T., and E. P. ODUM. 1955. Trophic structure and productivity of a windward coral reef community on Eniwetok Atoll. Ecological Monographs, vol. 25, pp. 291–320.

SARGENT, M. C., and T. S. AUSTIN. 1949. Organic productivity of an atoll. Transactions of the American Geophysical Union, vol. 30, pp. 245–249.

SCHIESSER, H. G. 1970. An inexpensive *in situ* pump for sampling shallow waters. Hawaii Institute of Geophysics Report 70-23.

STRICKLAND, J. D. H., and T. R. PARSONS. 1968. A practical handbook of seawater analysis. Bulletin of the Fisheries Research Board of Canada, no. 167.

VON ARX, W. S. 1954. Circulation systems of Bikini and Rongelap lagoons, Bikini and nearby atolls, Marshall Islands. U.S. Geological Survey Professional Paper 260-B, pp. 265–373.

WIENS, H. J. 1962. Atoll environment and ecology. New Haven, Yale University Press. 532 pp.